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Unified Structure in Quaternary Climate

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Abstract. The Quaternary climate record exhibits a structure of superimposed, aperiodic oscillations starting at the 11-yr sunspot cycle and spaced by powers of 2 in period through the major 90,000-yr glacial cycle. Climate cycles that do not fall in this structure typically correspond to harmonics of the structure oscillations. The inclusion of the known solar cycles and the presence of increased abundances of cosmogenic radionuclides at many structure periods suggest that the structure is related to long-period solar variability.

The Climate Record

Climatologists have recently noted that some climate oscillations occur at fractions—1/2, 1/4, 1/8, and 1/16—of the period of the 23-ky (ky = 1000 yr) Milankovitch precessional cycle [*Kerr*, 1996]. Curiously, when extrapolated downward, this sequence includes the periods of the known solar cycles: 1/256 coincides with the 88-yr Gleissburg solar cycle; 1/1024 is the 22-yr solar magnetic cycle; 1/2048 is the 11-yr sunspot cycle. Re-examination of data from numerous climate proxies (materials that carry the imprint of past climate) indicates that this relationship is pervasive. Swings in climate over time scales from the 11-yr sunspot cycle to the 90-ky glacial cycle tend to a unified geometric structure of superimposed, aperiodic oscillations spaced by powers of 2 in period.

Table 1 contains a partial list of climate cycles from the scientific literature that correspond to oscillations in the unified structure. The average oscillation periods of the structure are based on an estimate of 88.4 yr for the Gleissberg solar cycle [*Feynman*, 1988] (in yr): 11.05, 22.1, 44.2, 88.4, 177, 354, 707, 1414, 2830, 5660, 11.3k, 22.6k, 45.3k, and 90.5k. The reported climate-cycle periods do not exactly match the average structure periods because the oscillations are aperiodic and only have a tendancy to cycle at the average periods. Aperiodicity is indicated by oscillations occurring at varying frequencies (e.g., the tree-ring ^{14}C record shows cycles lasting from 150 to 220 yr [*Weiss*, 1990] and the Devils Hole record shows glacial cycles lasting from 79 ky to 128 ky [*Winograd et al.*, 1992]) and by oscillations appearing and disappearing over time (e.g., the 90-ky glacial cycle was inconsequential before ~700-ky ago [*Williams et al.*, 1988]).

To illustrate the unified structure, time series and power spectra for 3 climate proxies are presented in Figure 1: tree-ring growth indicies from California bristlecone pines [*Graybill et al.*, 1994], oxygen-isotope ratios (δ^{18}O) from Greenland ice core [*Dansgaard et al.*, 1993], and δ^{18}O in calcite from Devils Hole, Nevada [*Winograd et al.*, 1992]. These 3 climate proxies are selected here because they are from physically different sources, they describe variations at different timescales, and they were dated without using the Milankovitch cycles. Many important features of these spectra have been produced by other researchers (e.g., *Ditlevsen et al.* [1996]; *Imbrie et al.* [1993]). All of the structure peaks are visible, except perhaps for the weakest oscillations at 11, 22, and 44 yr (note the marked increase in power with period).

Intermediate peaks visible in Figure 1 can be explained as harmonics of the primary structure oscillations (harmonics are vibrations that occur in concert with and at integer multiples of the fundamental frequency; e.g., the overtones that accompany the note of a plucked guitar string). Consider a primary oscillation with period λ, frequency $f = 1/\lambda$, and harmonics at Nf (or λ/N) for $N > 1$. The important even harmonics, at $N = 2$ and $N = 4$ (harmonics typically fall off rapidly in amplitude with increasing N), are hidden by the primary, geometrically spaced oscillations in the structure; however, the important odd harmonics, at $N = 3$ and $N = 5$, occur between the primary oscillations and are visible. For example, the primary structure oscillation at $\lambda = 707$ yr generates 3^{rd} and 5^{th} harmonics with periods of 236 and 141 yr; peaks that correspond to these periods are visible in the bristlecone-pine spectrum. The large peaks in the Greenland ice-core spectrum at periods of 3.8 ky and 4.5 ky correspond to the 3^{rd} harmonic of the 11.3-ky oscillation and the 5^{th} harmonic of the 22.6-ky oscillation, respectively. This interpretation is supported by the scientific literature, where tree-ring growth is often reported to have cycles at about 7, 16, 30, 60, and 120 yr (e.g., *Briffa et al.* [1992]), marine δ^{18}O measurements are reported to show cycles at about 4 ky, 7 ky, 9 ky, and 16 ky [*Pestiaux et al.*, 1987; *Yiou et al.*, 1994], and ice-core hydrogen-isotope ratios (δ^2H) are reported to show cycles at 4.8 ky, 6.7 ky, 7.4-ky, and 8.7-ky [*Yiou et al.*, 1994]. All these cycles, with the sole exception of 6.7 ky, closely correspond to 3^{rd} or 5^{th} harmonics of primary structure oscillations.

Discussion

A possible cause of the unified structure involves the Milankovitch cycles—low-frequency variations in the Earth's orbital eccentricity, tilt, and precession. Many researchers have noted apparent harmonics and beats (beats are pulsations in amplitude that occur when oscillations of different frequencies overlap) in the climate record (e.g., *Pestiaux et al.* [1987]; *Yiou et al.* [1994]) and it is possible that the Milankovitch cycles propagate these high-frequency disturbances in the climate system. Except, harmonics are linearly related in frequency and hence cannot form a pattern

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Table 1. Abbreviated list of evidence corroborating structure oscillations (1k = 1000).

Ave. Structure Period (yr)	Climate Proxy	Reported Cycles (yr)	Reference
11.05, 22.1, 44.2	glacier dust	11—Peru, China	*Monastersky* [1996]
	El Niño frequency	∼22, ∼50, ∼90—global, Nile	*Anderson* [1992]
	tree-ring growth	∼22, 80–100—New Mexico	*D'Arrigo and Jacoby* [1991]
88.4	ice-core ^{18}O	78—Camp Century	*Dansgaard et al.* [1973]
	ice-core ^{10}Be	93—South Pole	*Raisbeck et al.* [1990]
177	varves	175—Castile formation (Permian)	*Anderson* [1982]
	ice-core ^{18}O	181—Camp Century	*Dansgaard et al.* [1973]
	tree-ring ^{14}C	208—La Jolla, Belfast	*Sonnet and Finney* [1990]
354	ice-core ^{18}O	350—Camp Century	*Dansgaard et al.* [1973]
	tree-ring ^{14}C	357—La Jolla, Belfast	*Sonnet and Finney* [1990]
707	tree-ring growth	∼700—Campito	*Burroughs* [1992]
	tree-ring ^{14}C	717—La Jolla, Belfast	*Sonnet and Finney* [1990]
1414	tree-ring growth	∼1400—Campito	*Burroughs* [1992]
	ice-core ^{10}Be & ^{14}C	1450—GISP2	*Kerr* [1996]
	marine lithic conc.	1470±500—N. Atlantic	*Bond et al.* [1997]
2830	glacier advance/retreat	∼2500 (Holocene)	*Burroughs* [1992]
	marine lithic conc.	∼2600 (Holocene)	*Monastersky* [1996]
	marine-sediment ^{18}O	2.6k, 2.7k, 3k—Indian Ocean	*Pestiaux et al.* [1987]
	varves	2700—Castile formation (Permian)	*Anderson* [1982]
5660	marine-sediment ^{18}O	several ∼5.6k—global	*Yiou et al.* [1994]
	marine-sediment ^{18}O	5.4k, 5.5k, 5.8k, 6k—Indian Ocean	*Pestiaux et al.* [1987]
11.3k	marine lithic conc.	11k±1k—NE Atlantic	*Heinrich* [1988]
	marine-sediment ^{18}O	several ∼11.3k—global	*Yiou et al.* [1994]
22.6k, 45.3k, 90.5k	varves	∼20k, ∼100k—Castile (Permian)	*Anderson* [1982]
	marine-sediment ^{18}O	23k, 41k, 100k—SPECMAP	*Imbrie et al.* [1984]

of oscillations spaced by powers of 2. Nor can beats form a geometric pattern; beats are also linearly related and, furthermore, beats cannot be seen in a power spectrum. Thus, as there are no other obvious mechanisms by which the Milankovitch cycles could generate the unified structure, their inclusion in, or extension of, the structure must be considered coincidental.

There are, however, reasons to believe that the unified structure is related to solar variability. (1) Observed solar cycles—i.e., the 11-yr sunspot, 22-yr magnetic, and 88-yr Gleissberg cycles—correspond to the short periods in the structure. (2) Abundances of cosmogenic radionuclides increase at several middle periods in the structure—e.g., 88.4, 177, 354, 707, and 1414 yr (Table 1). (3) The colder climate during the Little Ice Age coincided with an increase in cosmogenic radionuclide abundance and a reduction in solar activity, as indicated by a dearth of sunspots during the Maunder Minimum (about 1640 to 1710 AD) [*Eddy*, 1976]. (4) During the last glacial period (the 90-ky oscillation), cosmogenic radionuclides increased in abundance [*Plummer et al.*, 1997], while average global temperature decreased and glaciers advanced in both northern and southern hemispheres [*Broecker*, 1996].

Regarding this apparent solar influence, another possible cause of the structure is a high-frequency oscillation, such as the sunspot cycle, producing long-period subharmonics (subharmonics are vibrations that occur at lower frequencies than the fundamental frequency). Geometrically spaced subharmonics can be generated, as generic behavior, by systems known as forced nonlinear oscillators. The common situation is when a forced nonlinear oscillator undergoes "period doubling"—except period doubling produces periodic oscillations and the oscillations decrease in power with period [*Feigenbaum*, 1983]. Nonetheless, over limited intervals, when behaving chaotically, certain forced nonlinear oscillators can produce aperiodic subharmonics that tend to a powers-of-2 spacing and that increase in power with period. *Feynman and Gabriel* [1990] note that the 88-yr Gleissburg cycle is a subharmonic of the sunspot cycle and suggest that the solar dynamo operates in a chaotic regime near the period-doubling regime. Other solar processes can act as nonlinear oscillators and can be forced at the sunspot cycle—e.g., convective heat transfer and pulsations of gaseous spheres—but further discussion must be left for a later report.

Implications

Quaternary climate exhibits a unified structure that spans virtually all time scales. This conclusion is based on the work of many researchers. The unified nature of the structure argues for a single cause, and evidence suggests that the cause is related to the Sun. Other climate drivers, such as the Milankovitch cycles and ocean currents, could reinforce or extend the structure, but probably only by coincidence. And, although the tendency toward a powers-of-2 oscillation spacing appears to be robust, the aperiodicity and the increasing power with period imply that the structure is chaotic and that climate, like weather, is fundamentally unpredictable.

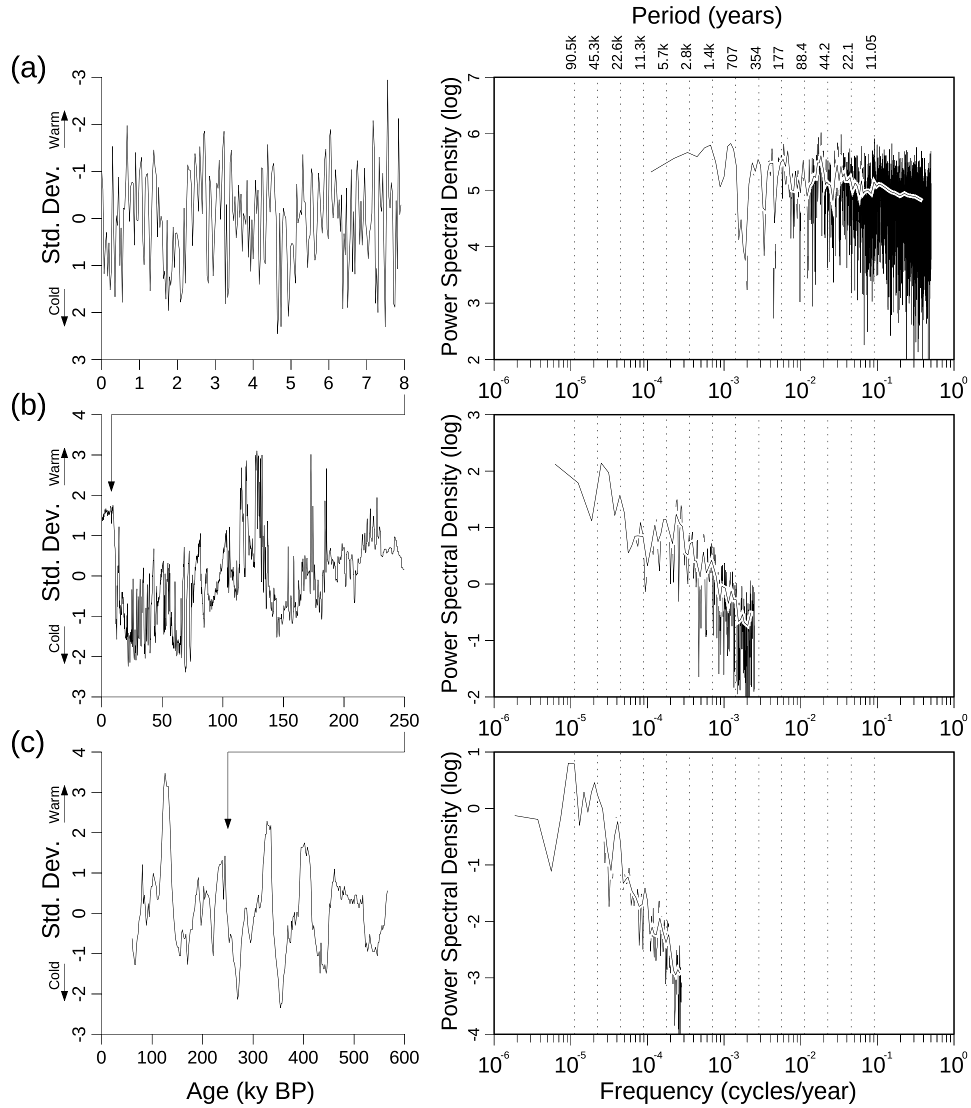

Figure 1. Time series (left) and power spectra (right) for 3 climate proxies showing the tendency to produce oscillations spaced by powers of 2 in period: (a) tree-ring growth indices from the Methuselah Walk bristlecone pines (California, US) [*Graybill et al.*, 1994]; (b) δ^{18}O from GRIP ice core (Greenland) [*Dansgaard et al.*, 1993]; and (c) δ^{18}O from Devils Hole calcite (Nevada, US) [*Winograd et al.*, 1992]. The time series for the Methuselah Walk data has been smoothed with a 32-point binomial running average [*Burroughs*, 1992]. The GRIP spectrum includes only the most recent 104 ky of the data. The smoothed curves that overlay the spectra were created by applying a binomial running average to the spectrum, with repeated averaging at higher frequencies.

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